3 WHAT HAPPENS TO STRUCTURES WHEN THE GROUND MOVES?

". . . the road was swaying from side to side. . . . there was great, dramatic side to side movement. There was also up and down movement. The car felt like it was bouncing up and down, but the side to side movement was greater than the up and down movement. . . ."
– report by survivor of the Cypress Freeway collapse, Loma Prieta earthquake, 1989.

This book focuses on the risk posed by and to buildings in earthquakes and the steps that can be taken through building regulation and voluntary design education to reduce this risk. First and foremost is the risk to human life in houses, at offices, in schools, in shops and malls, at places of recreation where thousands of people may gather to watch a sporting event or concert, and elsewhere. Beyond the risk to life is the economic and social disruption caused by an earthquake; even moderate earthquakes can result in the loss of many homes, jobs, investments, and community resources.

While earthquakes cause damage and disruption to utilities such as water and power services, these problems are relatively short-lived because utility companies encounter outages and disruption on a normal basis and are equipped to deal with them. Earthquakes may cause severe damage to transportation systems such as railroads and freeways, and collapsing bridges and overpasses may cause injury and death – like that which occurred in the 1989 Loma Prieta earthquake and the 1985 Northridge earthquake in California. These are special problems, however, and need to be dealt with primarily by state transportation agencies. In essence, improving the seismic resistance of buildings is seen as the key to reducing the earthquake threat to the public at large and to the community.

Issues of health and safety in buildings typically are regulated by building codes written to ensure that some minimal standards of design and construction are adhered to for potentially dangerous aspects of buildings. These codes generally establish such things as maximum loads so that floors of a building will not collapse because they are overloaded with people and equipment and the minimum height of a balcony railing so people will not fall over it. These regulations ensure a common minimum standard of safety and mean that building designers work to meet common criteria and do not have to try and solve all the problems of building design on their own every time a new building is planned.

In regions of the United States such as California and Alaska where earthquakes are frequent, seismic codes have been developed and enforced by local communities for many decades, and most existing buildings have been designed with earthquakes in mind. However, since the "science" of earthquake-resistant building design is a relatively new field (the first seismic codes were enforced in California only in 1927), buildings designed to earlier codes are not now necessarily assumed to be safe, and work continues in these regions to, in some instances, strengthen and improve buildings designed to meet the provisions of the earlier codes and to improve the codes.

In regions of the country where the seismic threat has not been accompanied by the continual occurrence of earthquakes the story of different. There may be large inventories of buildings at risk that were designed with no consideration of the seismic problem, and new buildings may still be constructed every year that add to this inventory. When the inevitable large or even moderate earthquake occurs , these buildings may suffer devastating losses. For example, earthquake experts cite the terrible damage to the city of Kobe in Japan where over 5,000 people lost their lives in the January 1995 earthquake. This region had been clearly earmarked as an earthquake hazard area by the seismologists and earth scientists, but because a severe earthquake had not affected the city for several hundred years, its buildings (although designed to a seismic code) were vulnerable and its population and government emergency response services were largely unprepared.

For communities where a significant earthquake has not occurred in the lifetime of its citizens, the experience of an earthquake is hard to imagine and it is difficult to visualize what an earthquake would do to familiar buildings and other structures. This chapter of *Seismic Considerations for Communities at Risk* is intended to give readers some idea of the sort of damage that earthquakes do to buildings. The photographs generally show the results of California and Alaska earthquakes and, for the most part, show older buildings designed to lower-than-present-day standards or, in the case of unreinforced masonry buildings, designed prior to the adoption of seismic codes.

As noted earlier, in the less active seismic regions of the country, limited resources may permit the seismic strengthening of only a few critical or valuable existing buildings, but such regions quite likely have the advantage of time – that is, a crippling earthquake is less likely to occur in the near future, thus giving communities in these regions the opportunity to at least ensure that new buildings are designed to meet up-to-date seismic standards while ridding themselves of the most hazardous existing buildings through the normal cycle of building decay, removal, and replacement.

UNREINFORCED MASONRY BUILDINGS

Unreinforced masonry buildings have long been identified as performing very poorly in earthquakes. Unreinforced masonry buildings typically have brick or block bearing walls and wood-framed floors and roofs. The floors and roofs tend to pull away from the walls and collapse; the upper portions of walls, particularly parapets, tend to fall and, depending on the quality and age of the mortar, walls tend to disintegrate.

In California, the state requires that all cities develop an inventory of their unreinforced masonry buildings and devise a plan for their demolition or improvement. In Los Angeles, an ordinance was enforced in 1981 that required all owners of unreinforced masonry buildings to demolish or strengthen them. By 1995, essentially all 8,000 buildings of this type had either been demolished or strengthened. The 1994 Northridge earthquake showed a notable improvement in the performance of these types of buildings compared to earlier earthquakes – no one was killed and injuries were minimal. San Francisco and a number of other California cities now have similar ordinances in effect.

Typical damage to unreinforced masonry buildings on the main street of Coalinga, California, after the 1983 earthquake (Chris Arnold, Building Systems Development, Inc.).

Typical upper wall failures after the 1987 earthquake in Whittier, California (Chris Arnold, Building Systems Development, Inc.).

Upper wall failure in San Francisco, California, after the 1989 Loma Prieta earthquake; this collapse killed six people in cars parked beneath the wall (Chris Arnold, Building Systems Development, Inc.).

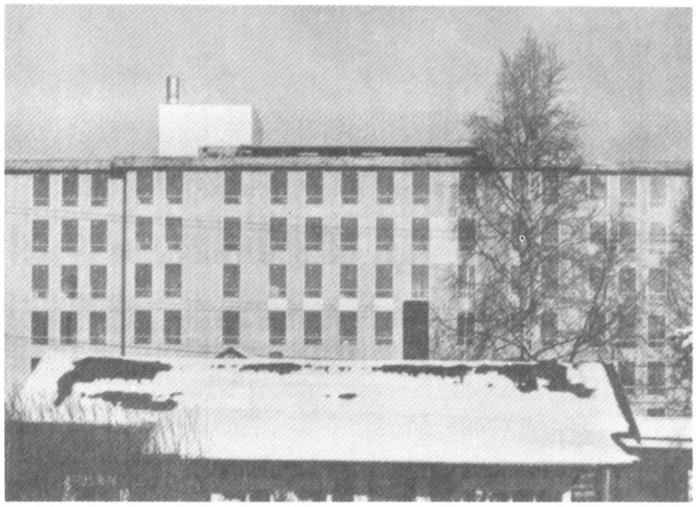
REINFORCED CONCRETE BUILDINGS

Older reinforced concrete structures designed before the characteristics of the material were fully understood have suffered severe damage in earthquakes. Unless heavily reinforced with steel, concrete is a brittle material that tends to fail without warning. In foreign countries, earthquakes have caused many total collapses but, in California and Alaska, total collapses have been few. Irreparable damage, however, has been significant. Frame structures with few structural walls suffer the most damage, and the problem is less acute for structures with many concrete walls. Seismic codes in force since the 1970s require special reinforcing that greatly reduces the possibility of these brittle failures.

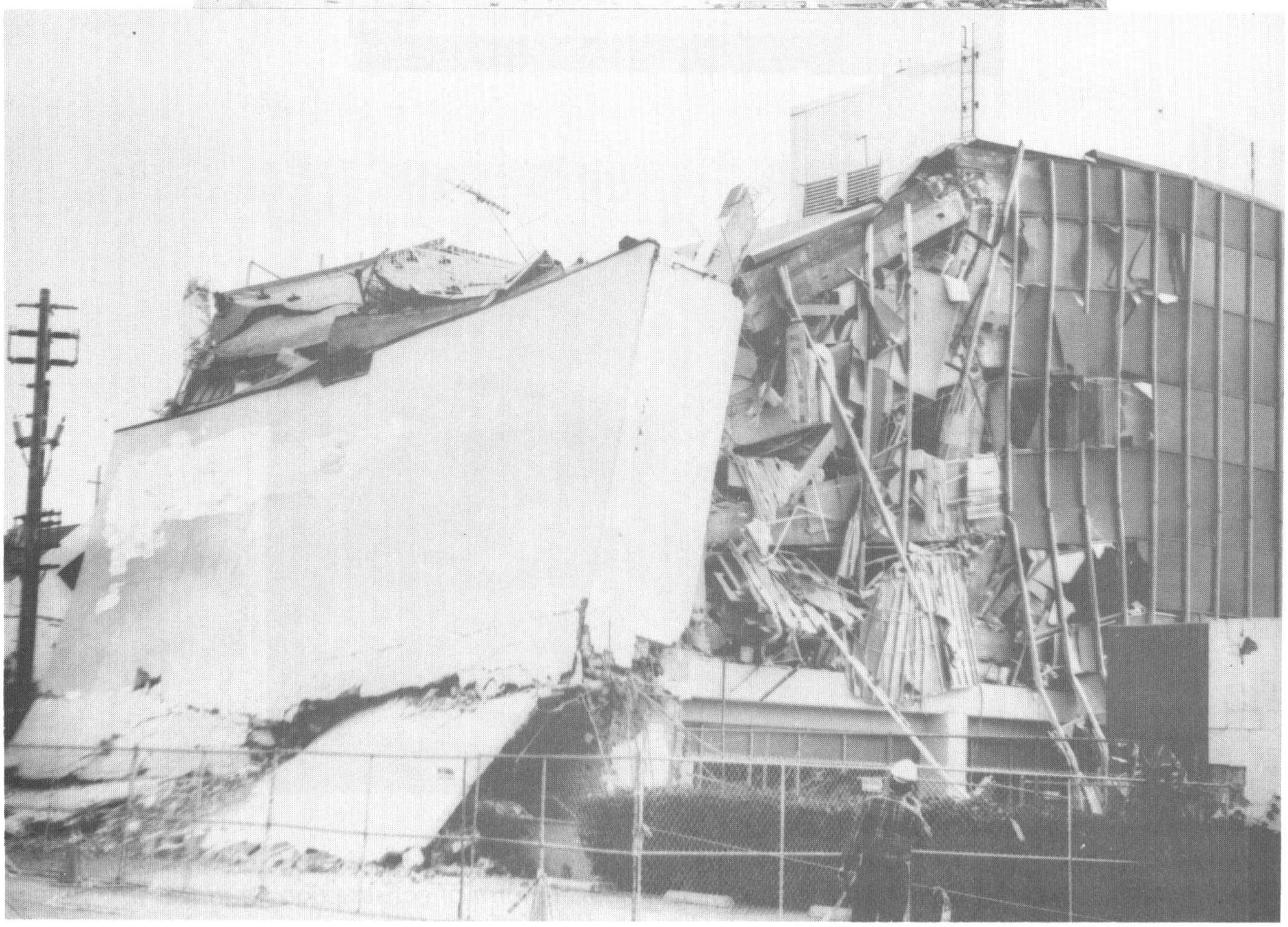
Precast concrete structures and the "tilt-up" type of reinforced concrete construction often used for industrial and commercial buildings also have suffered badly in earthquakes. In these types of structures, the damage has been due primarily to inadequate connections between the precast members or between the walls and roof.

Olive View hospital was badly damaged in the 1971 earthquake in San Fernando, California, primarily because of a "soft story" condition – that is, its lower two floors were much more flexible than the upper floors causing failure where the structure changed from flexible columns to stiff walls.

Staircase towers at Olive View hospital collapsed, rendering evacuation of patients much more difficult; two patients were killed at this hospital because their life-support system failed, and one maintenance worker was killed by a falling canopy.



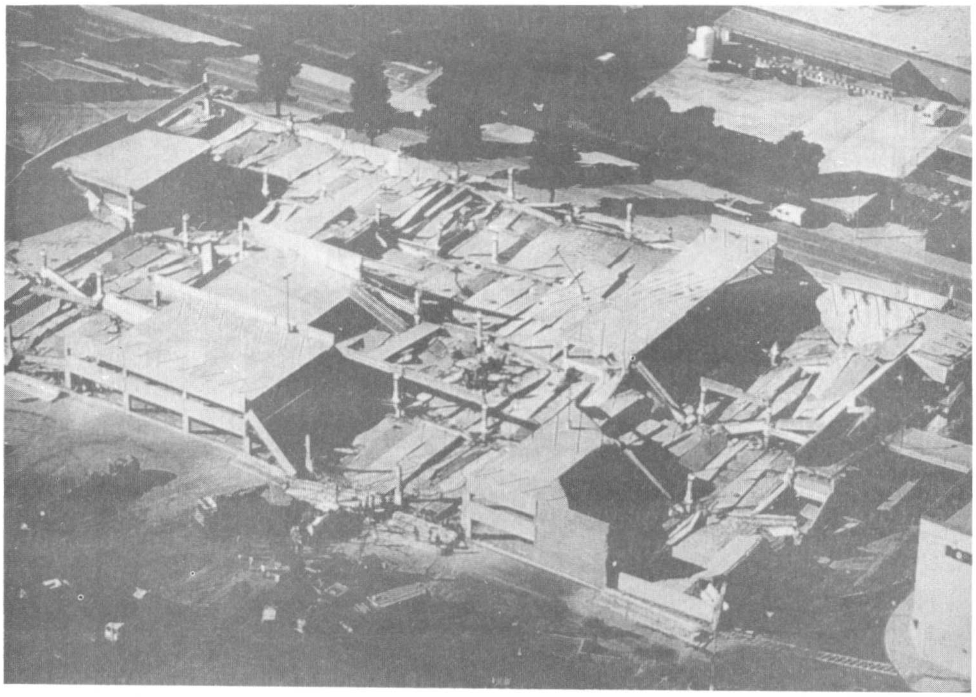
The six-story Four Seasons apartment building in Anchorage, Alaska, before and after the 1994 earthquake. It was designed with pre-cast lift-slab floors (a form of construction no longer in use). The earthquake forces were resisted by two poured-in-place reinforced concrete towers. However, in the 1964 Anchorage earthquake, both towers proved to have inadequate strength to resist the lateral forces; they fractured at the first floor and toppled over; when the slabs tore loose from the towers, the whole building collapsed. Fortunately the building was still under construction (though structurally complete) and was unoccupied.



This older medical office building suffered partial collapse at each end and the entire second floor collapsed as a result of the 1994 earthquake in Northridge, California. The building was unoccupied due to the early morning hour at which the quake occurred (Chris Arnold, Building Systems Development, Inc.).

This office building lost its end wall in the 1994 Northridge earthquake; the end wall was nonstructural and inadequately attached to the building. The comparable wall at the other end of the building was damaged but did not detach (Chris Arnold, Building Systems Development, Inc.).

This large commercial building, which had tilt-up concrete walls and a wood roof, lost its end wall in the 1994 Northridge earthquake. The wall was inadequately attached to the roof and movement of the heavy storage racks that now appear to support the roof may have helped to push the wall down (Chris Arnold, Building Systems Development, Inc.).



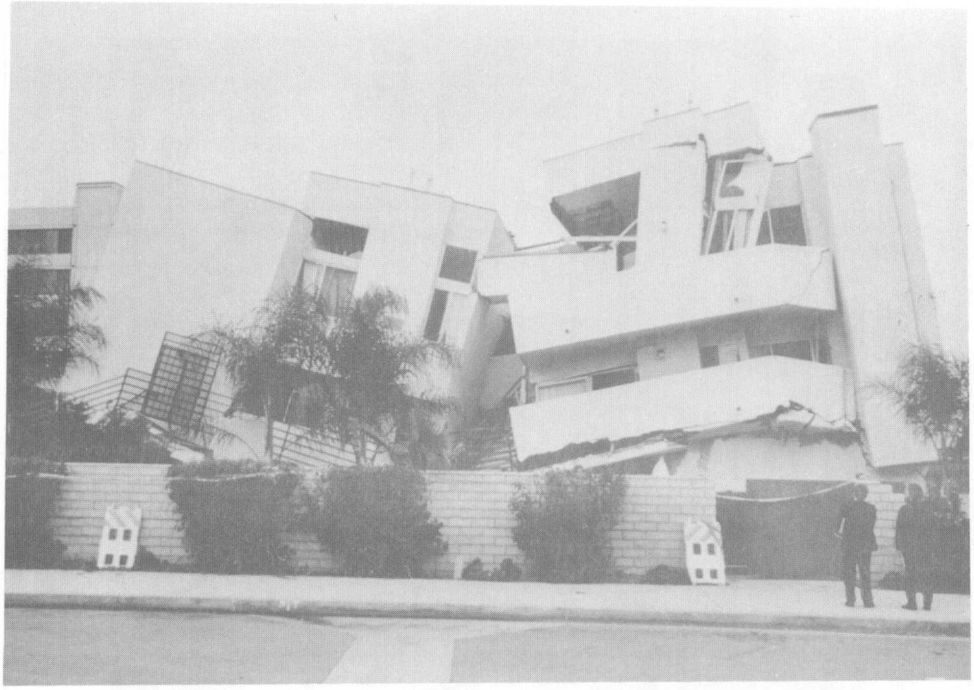
Failure of a precast concrete parking structure in the Northridge earthquake; the joints were unable to resist the earthquake forces (Earthquake Engineering Research Institute).

COMMERCIAL AND RESIDENTIAL BUILDINGS

This steel frame and reinforced masonry commercial building suffered a partial collapse in the 1994 Northridge earthquake; it had to be demolished (Chris Arnold, Building Systems Development, Inc.).

This older San Francisco apartment house has a soft story because the garage floor is much weaker than the upper floors. It almost collapsed in the 1989 Loma Prieta earthquake (Chris Arnold, Building Systems Development, Inc.).

This apartment house had a soft first story that completely disappeared during the 1994 Northridge earthquake crushing a number of parked cars. This was a fairly new building, but the earthquake found the weak points of the seismic design (Chris Arnold, Building Systems Development, Inc.).



Northridge earthquake damage to another new apartment house with a soft first story created by ground floor parking (Chris Arnold, Building Systems Development, Inc.).

The Northridge Meadows apartment house with a soft first story. It collapsed in the Northridge earthquake and 16 people were killed (Earthquake Engineering Research Institute).

A common example of damage to an older single-family residence as a result of the 1983 earthquake in Coalinga, California. The wood frame was too weak to support the heavy roof (Chris Arnold, Building Systems Development, Inc.).

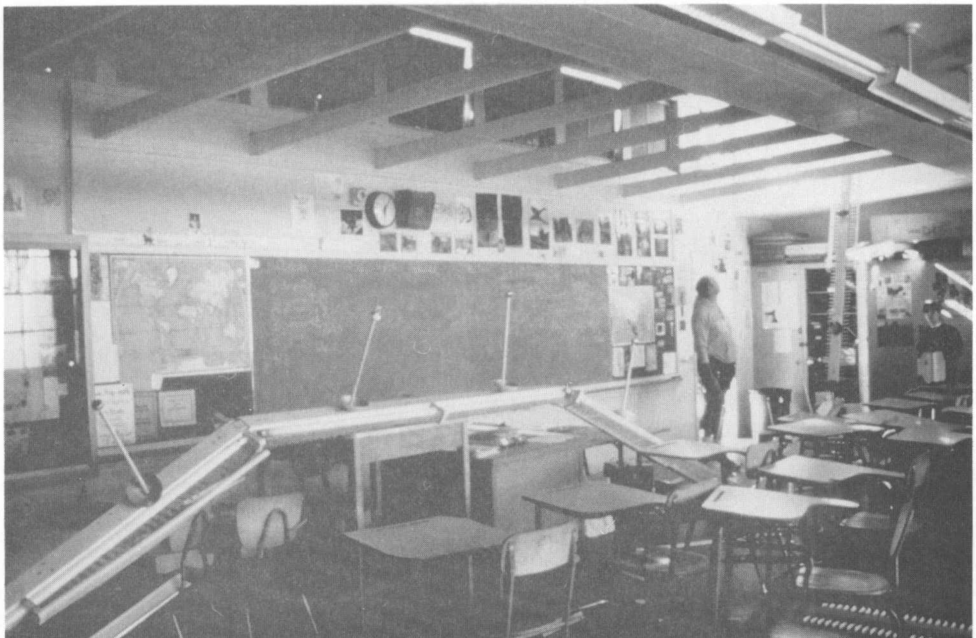
Typical damage to a single-family residence caused by inadequate bracing of the "cripple wall" – the short stud wall between the foundation and the first floor. This type of failure causes costly damage but the problem can be solved easily by bracing the walls with plywood (Chris Arnold, Building Systems Development, Inc.).

NONSTRUCTURAL DAMAGE

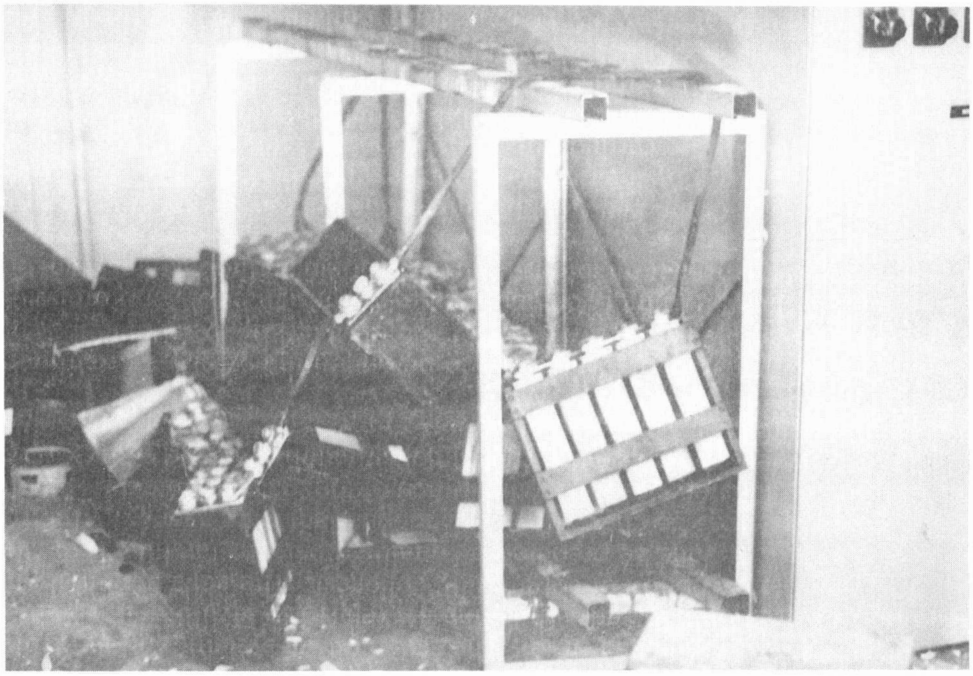
In a typical building the structural components (floor and roof structure, bearing walls, columns, beams, and foundations) account for only about 15 to 20 of the construction cost: the nonstructural architectural, mechanical and electrical components make up between 70 and 85 percent of the building's replacement value.

All these nonstructural components are subject to damage, either directly due to shaking or because of distortion due to movement of the structure. Building occupants are particularly vulnerable to nonstructural damage, and people outside have been injured and even killed by falling parapets and glass. Fires and explosions have been caused by damaged mechanical and electrical equipment. Moreover, nonstructural damage is very costly to repair, and can occur when there is little or no structural damage. It has been estimated that, in recent earthquakes, many buildings with no serious structural damage have suffered considerable nonstructural damage, sometimes totaling as much as 50 per cent of the building's replacement value.

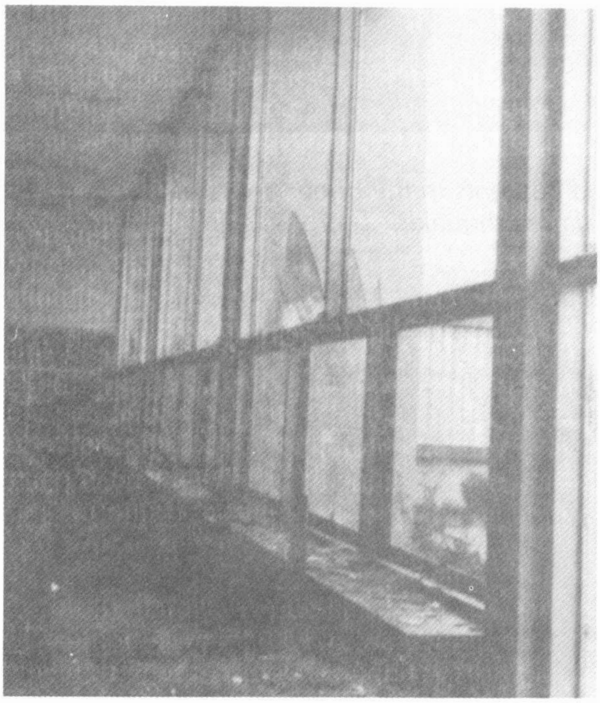
In addition, nonstructural damage causes operational disruption, and a building may be unusable for months while nonstructural damage is repaired. This may represent a crippling financial loss to the owners and employees.



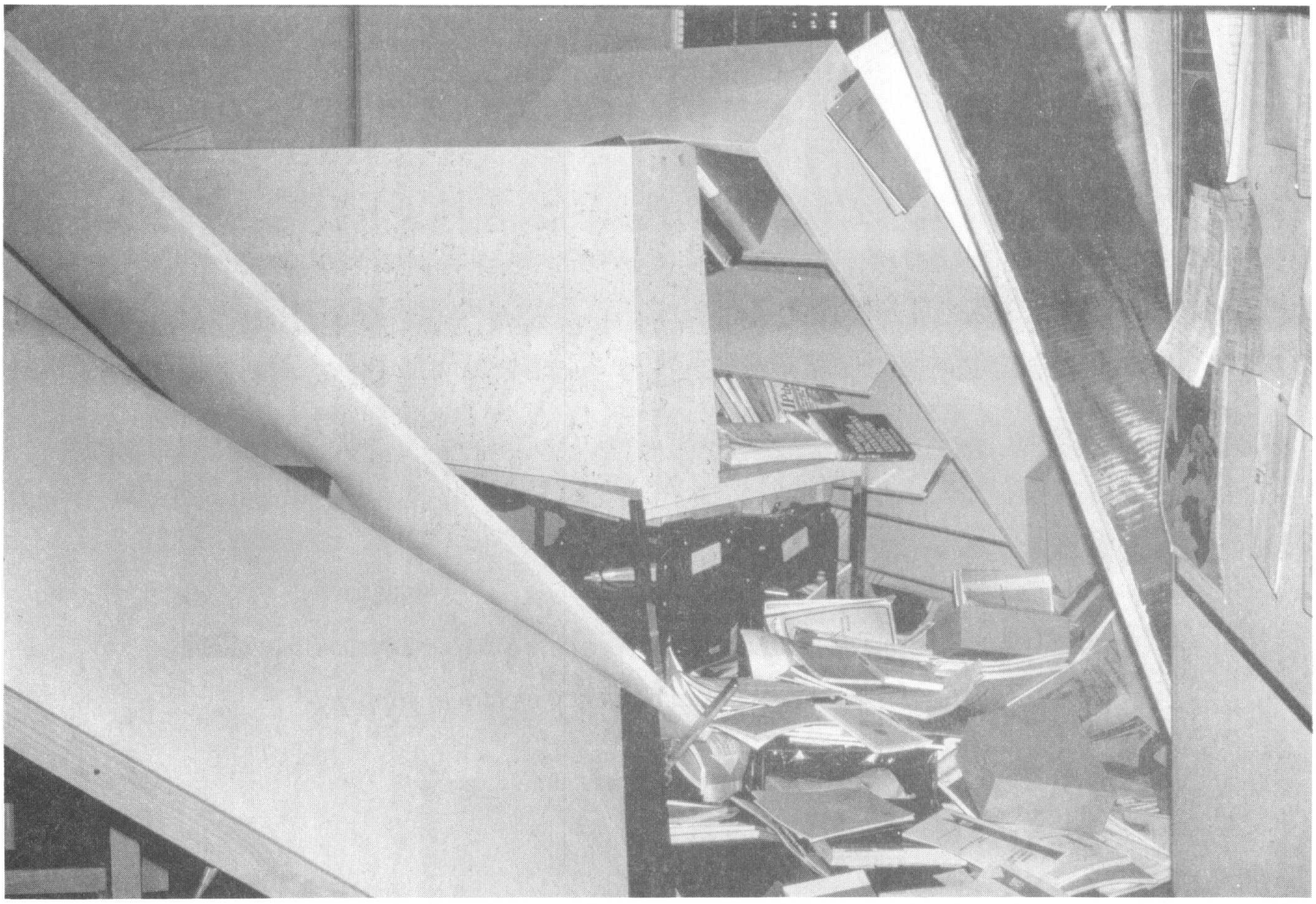
Fallen light fixtures in a school after the 1994 Northridge earthquake (Gary McGavin).



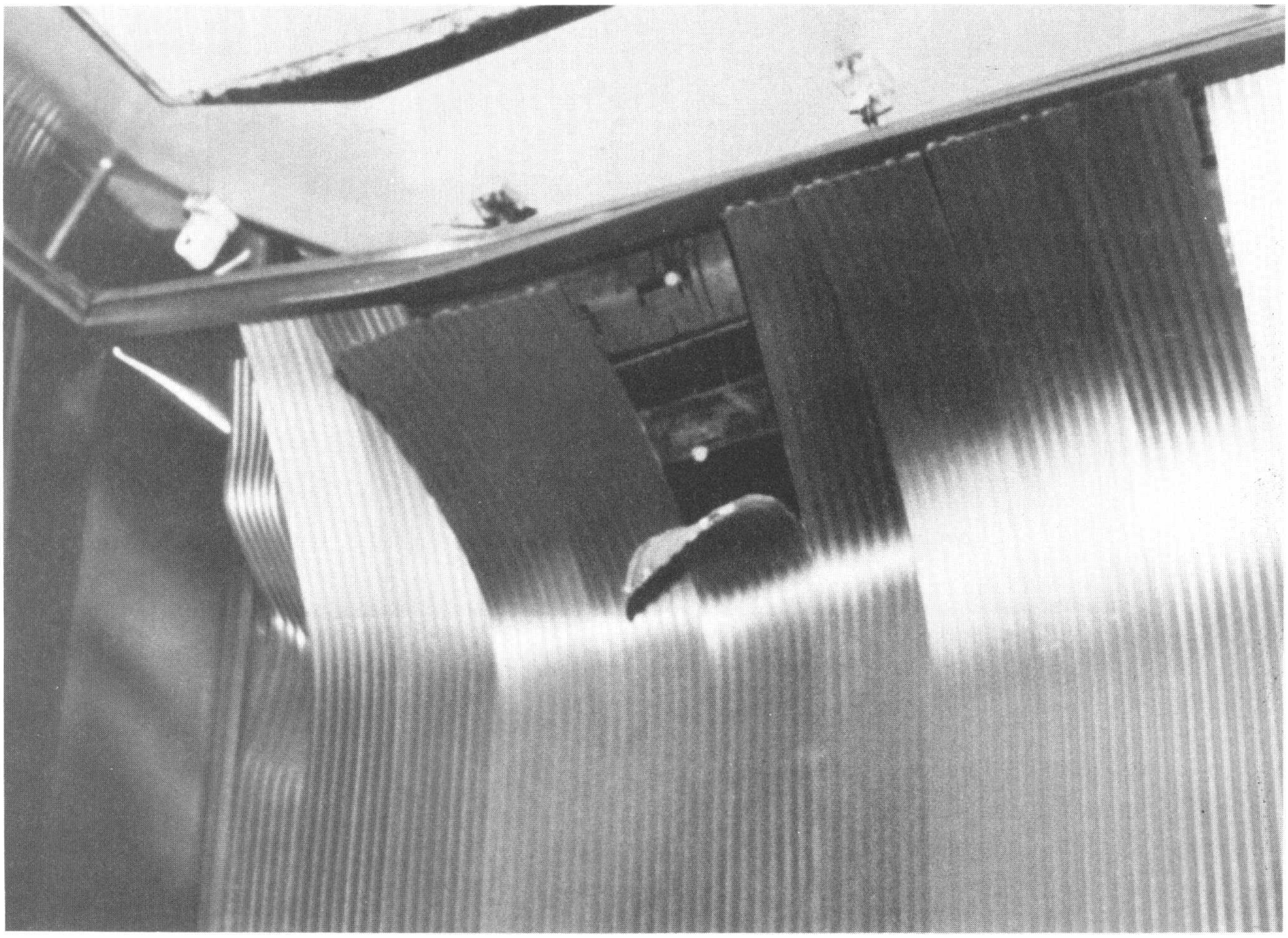
Collapsed battery racks for emergency electrical supply.



Damage to junior high school classroom in 1983 Coalinga earthquake. If the students had been in the room, serious injuries might have occurred.



Damage to the furniture and contents in the upper floors of an open planned office after the 1984 Morgan Hill, California, earthquake. There was no structural damage to this building.

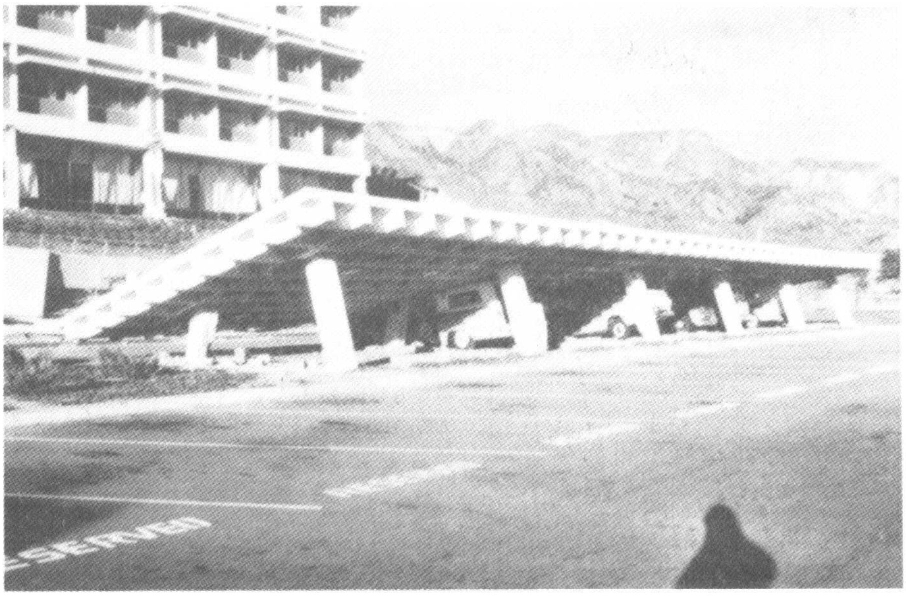


Earthquake damage to an elevator.

Exit corridor in Olive View Hospital after the 1971 San Fernando earthquake.

Stairway blocked by falling wall and ceiling materials.

Hallway blocked by fallen ceiling materials.



Parking canopy collapsed on ambulances at Olive View Hospital as a result of the 1971 San Fernando earthquake.